

On an Auxiliary Function for Log-Density Estimation

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July 2008, minor revisions in January 2016

Abstract

In this note we provide explicit expressions and expansions for a special function J which appears in nonparametric estimation of log-densities. This function returns the integral of a log-linear function on a simplex of arbitrary dimension. In particular it is used in the *R*-package *LogCondDEAD* by Cule et al. (2007).

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1 Introduction

Suppose one wants to estimate a probability density f on a certain compact region $C \subset \mathbb{R}^d$, based on an empirical distribution \hat{P} of a sample from f . One possibility is to embed C into a union

$$S = \bigcup_{j=1}^m S_j$$

of simplices $S_j \subset \mathbb{R}^d$ with pairwise disjoint interior. By a simplex in \mathbb{R}^d we mean the convex hull of $d + 1$ points. Then we consider the family $\mathcal{G} = \mathcal{G}(S_1, \dots, S_m)$ of all continuous functions $\psi : S \rightarrow \mathbb{R}$ which are linear on each simplex S_j . Now

$$\hat{\psi} := \arg \max_{\psi \in \mathcal{G}} \left(\int_S \psi d\hat{P} - \int_S \exp(\psi(x)) dx \right) \quad (1)$$

defines a maximum likelihood estimator $\hat{f} := \exp(\hat{\psi})$ of a probability density on S , based on \hat{P} . For existence and uniqueness of this estimator see, for instance, Cule et al. (2008).

To compute $\hat{\psi}$ explicitly, note that $\psi \in \mathcal{G}$ is uniquely determined by its values at the corners (extremal points) of all simplices S_j , and $\int \psi d\hat{P}$ is a linear function of these values. The second integral in (1) may be represented as follows: Let S_j be the convex hull of $\mathbf{x}_{0j}, \mathbf{x}_{1j}, \dots, \mathbf{x}_{dj} \in \mathbb{R}^d$, and set $y_{ij} := \psi(\mathbf{x}_{ij})$. Then

$$\int_S \exp(\psi(x)) dx = \sum_{i=1}^m \int_{S_i} \exp(\psi(x)) dx = \sum_{i=1}^m D_j \cdot J(y_{0j}, y_{1j}, \dots, y_{dj}),$$

where

$$D_j := \det[\mathbf{x}_{1j} - \mathbf{x}_{0j}, \mathbf{x}_{2j} - \mathbf{x}_{0j}, \dots, \mathbf{x}_{dj} - \mathbf{x}_{0j}],$$

while $J(\cdot)$ is an auxiliary function defined and analyzed subsequently.

2 The special function $J(\cdot)$

2.1 Definition of $J(\cdot)$

For $d \in \mathbb{N}$ let

$$\mathcal{T}_d := \left\{ \mathbf{u} \in (0, 1)^d : \sum_{i=1}^d u_i < 1 \right\}.$$

Then for $y_0, y_1, \dots, y_d \in \mathbb{R}$ we define

$$J(y_0, y_1, \dots, y_d) := \int_{\mathcal{T}_d} \exp\left((1 - u_+)y_0 + \sum_{i=1}^d u_i y_i\right) d\mathbf{u}$$

with $u_+ := \sum_{i=1}^d u_i$.

Standard considerations in connection with beta- and gamma-distributions as described in Section 6 reveal the following alternative representation:

$$J(y_0, y_1, \dots, y_d) := \frac{1}{d!} \mathbb{E} \exp\left(\sum_{i=0}^d B_i y_i\right)$$

with $B_i = B_{d,i} := E_i / \sum_{s=0}^d E_s$ and stochastically independent, standard exponential random variables E_0, E_1, \dots, E_d . This representation shows clearly that $J(\cdot)$ is symmetric in its arguments.

An often useful identity is

$$J(y_0, y_1, \dots, y_d) = \exp(y_*) J(y_0 - y_*, y_1 - y_*, \dots, y_d - y_*) \quad \text{for any } y_* \in \mathbb{R}. \quad (2)$$

2.2 A first recursion formula

For $d = 1$ one can compute $J(y_0, y_1)$ explicitly:

$$J(y_0, y_1) = \int_0^1 \exp((1 - u)y_0 + uy_1) du = \begin{cases} \frac{\exp(y_1) - \exp(y_0)}{y_1 - y_0} & \text{if } y_0 \neq y_1, \\ \exp(y_0) & \text{if } y_0 = y_1. \end{cases}$$

For $d \geq 2$ one may use the following recursion formula:

$$J(y_0, y_1, \dots, y_d) = \begin{cases} \frac{J(y_1, y_2, \dots, y_d) - J(y_0, y_2, \dots, y_d)}{y_1 - y_0} & \text{if } y_0 \neq y_1, \\ \frac{\partial}{\partial y_1} J(y_1, y_2, \dots, y_d) & \text{if } y_0 = y_1. \end{cases} \quad (3)$$

Since $J(y_0, y_1, \dots, y_d)$ is continuous in y_0, y_1, \dots, y_d , it suffices to verify (3) in case of $y_0 \neq y_1$. We may identify \mathcal{T}_d with the set $\{(v, \mathbf{u}) : \mathbf{u} \in \mathcal{T}_{d-1}, v \in (0, 1 - u_+)\}$. Then it follows from Fubini's theorem that

$$\begin{aligned}
& J(y_0, y_1, \dots, y_d) \\
&= \int_{\mathcal{T}_{d-1}} \int_0^{1-u_+} \exp\left((1-u_+-v)y_0 + vy_1 + \sum_{i=2}^d u_{i-1}y_i\right) dv d\mathbf{u} \\
&= \int_{\mathcal{T}_{d-1}} \left(\frac{\exp((1-u_+-v)y_0 + vy_1 + \sum_{i=2}^d u_{i-1}y_i)}{y_1 - y_0} \right) \Big|_{v=0}^{1-u_+} d\mathbf{u} \\
&= \int_{\mathcal{T}_{d-1}} \frac{\exp((1-u_+)y_1 + \sum_{i=2}^d u_{i-1}y_i) - \exp((1-u_+)y_0 + \sum_{i=2}^d u_{i-1}y_i)}{y_1 - y_0} d\mathbf{u} \\
&= \frac{J(y_1, y_2, \dots, y_d) - J(y_0, y_2, \dots, y_d)}{y_1 - y_0}.
\end{aligned}$$

2.3 Another recursion formula

It is well-known that for any integer $0 \leq j < d$,

$$\left(\frac{E_i}{\sum_{s=0}^j E_s} \right)_{i=0}^j, \quad B := \frac{\sum_{i=0}^j E_i}{\sum_{s=0}^d E_s}, \quad \left(\frac{E_i}{\sum_{s=j+1}^d E_s} \right)_{i=j+1}^d$$

are stochastically independent with $B \sim \text{Beta}(j+1, d-j)$; see also Section 6. Hence we end up with the following recursive identity:

$$\begin{aligned}
& J(y_0, y_1, \dots, y_d) \\
&= \frac{j!(d-j-1)!}{d!} \mathbb{E}(J(By_0, \dots, By_j)J((1-B)y_{j+1}, \dots, (1-B)y_d)) \\
&= \int_0^1 u^j (1-u)^{d-j-1} J(uy_0, \dots, uy_j)J((1-u)y_{j+1}, \dots, (1-u)y_d) du
\end{aligned}$$

with

$$J(r) := \exp(r).$$

Here we used the well-known identity

$$\int (1-u)^\ell u^m du = \frac{\ell!m!}{(\ell+m+1)!} \quad \text{for integers } \ell, m \geq 0. \tag{4}$$

Plugging in $j = d-1$ into the previous recursive equation leads to

$$J(y_0, y_1, \dots, y_d) = \int_0^1 u^{d-1} J(uy_0, \dots, uy_{d-1}) \exp((1-u)y_d) du. \tag{5}$$

3 An expansion for $J(\cdot)$

With $\bar{y} := (d+1)^{-1} \sum_{i=0}^d y_i$ and $z_i := y_i - \bar{y}$ one may write

$$J(y_0, y_1, \dots, y_d) = \exp(\bar{y}) J(z_0, z_1, \dots, z_d)$$

by virtue of (2). Note that $z_+ := \sum_{i=0}^d z_i = 0$. As $\mathbf{z} := (z_i)_{i=0}^d \rightarrow \mathbf{0}$,

$$\begin{aligned} d! J(z_0, z_1, \dots, z_d) \\ = 1 + \sum_{i=0}^d \mathbb{E}(B_i) z_i + \frac{1}{2} \sum_{i,j=0}^d \mathbb{E}(B_i B_j) z_i z_j + \frac{1}{6} \sum_{i,j,k=0}^d \mathbb{E}(B_i B_j B_k) z_i z_j z_k + O(\|\mathbf{z}\|^4). \end{aligned}$$

It follows from Lemma 6.1 that

$$\mathbb{E}\left(\prod_{i=0}^d B_i^{k_i}\right) = \prod_{i=0}^d k_i! / [d + k_+]_{k_+} \quad \text{for integers } k_0, k_1, \dots, k_d \geq 0.$$

In particular,

$$\begin{aligned} \mathbb{E}(B_0) &= \frac{1}{d+1}, \\ \mathbb{E}(B_0^2) &= \frac{2}{[d+2]_2}, \quad \mathbb{E}(B_0 B_1) = \frac{1}{[d+2]_2}, \\ \mathbb{E}(B_0^3) &= \frac{6}{[d+3]_3}, \quad \mathbb{E}(B_0^2 B_1) = \frac{2}{[d+3]_3}, \quad \mathbb{E}(B_0 B_1 B_2) = \frac{1}{[d+3]_3}. \end{aligned}$$

Consequently, $\sum_{i=0}^d \mathbb{E}(B_i) z_i = \mathbb{E}(B_0) z_+ = 0$,

$$\begin{aligned} [d+2]_2 \sum_{i,j=0}^d \mathbb{E}(B_i B_j) z_i z_j &= \sum_{i,j=0}^d (1_{[i=j]} \cdot 2 + 1_{[i \neq j]}) z_i z_j \\ &= \sum_{i,j=0}^d (1_{[i=j]} + 1) z_i z_j \\ &= \sum_{i=0}^d z_i^2 + z_+^2 \\ &= \sum_{i=0}^d z_i^2, \end{aligned}$$

and

$$\begin{aligned}
& [d+3]_3 \sum_{i,j,k=0}^d \mathbb{E}(B_i B_j B_k) z_i z_j z_k \\
&= \sum_{i,j,k=0}^d (1_{[i=j=k]} \cdot 6 + 1_{[\#\{i,j,k\}=2]} \cdot 2 + 1_{[\#\{i,j,k\}=3]}) z_i z_j z_k \\
&= \sum_{i,j,k=0}^d (1_{[i=j=k]} \cdot 5 + 1_{[\#\{i,j,k\}=2]} + 1) z_i z_j z_k \\
&= 5 \sum_{i=0}^d z_i^3 + 3 \sum_{s,t=0}^d 1_{[s \neq t]} z_s^2 z_t + z_+^3 \\
&= 5 \sum_{i=0}^d z_i^3 + 3 \sum_{s=0}^d z_s^2 z_+ - 3 \sum_{s=0}^d z_s^3 + z_+^3 \\
&= 2 \sum_{i=0}^d z_i^3.
\end{aligned}$$

Consequently,

$$J(y_0, y_1, \dots, y_d) = \exp(\bar{y}) \left(\frac{1}{d!} + \frac{1}{2(d+2)!} \sum_{i=0}^d z_i^2 + \frac{1}{3(d+3)!} \sum_{i=0}^d z_i^3 + O(\|z\|^4) \right). \quad (6)$$

4 A recursive implementation of $J(\cdot)$ and its partial derivatives

By means of (3) and the Taylor expansion (6) one can implement the function $J(\cdot)$ in a recursive fashion. In what follows we use the abbreviation

$$y_{a:b} = \begin{cases} (y_a, \dots, y_b) & \text{if } a \leq b \\ () & \text{if } a > b \end{cases}$$

To compute $J(y_{0:d})$ we assume without loss of generality that $y_0 \leq y_1 \leq \dots \leq y_d$. It follows from (3) and symmetry of $J(\cdot)$ that

$$J(y_{0:d}) = \frac{J(y_{1:d}) - J(y_{0:d-1})}{y_d - y_0}$$

if $y_0 \neq y_d$. This formula is okay numerically if $y_d - y_0$ is not too small. Otherwise one should use (6). This leads to the the pseudo code in Table 1.

To avoid messy formulae, one can express partial derivatives of $J(\cdot)$ in terms of higher order versions of $J(\cdot)$ by means of the recursion (3). For instance,

$$\begin{aligned}
\frac{\partial J(y_{0:d})}{\partial y_0} &= \lim_{\epsilon \rightarrow 0} \frac{J(y_0 + \epsilon, y_{1:d}) - J(y_0, y_{1:d})}{\epsilon} \\
&= \lim_{\epsilon \rightarrow 0} J(y_0, y_0 + \epsilon, y_{1:d}) \\
&= J(y_0, y_0, y_{1:d}).
\end{aligned}$$

<p>Algorithm $J \leftarrow \mathbf{J}(y, d, \epsilon)$</p> <p>if $y_d - y_0 < \epsilon$ then</p> <p style="padding-left: 20px;">$\bar{y} \leftarrow \sum_{i=0}^d y_i / (d + 1)$</p> <p style="padding-left: 20px;">$z_2 \leftarrow \sum_{i=0}^d (y_i - \bar{y})^2 / 2$</p> <p style="padding-left: 20px;">$z_3 \leftarrow \sum_{i=0}^d (y_i - \bar{y})^3 / 3$</p> <p style="padding-left: 20px;">$J \leftarrow \exp(\bar{y}) (1/d! + z_2/(d + 2)! + z_3/(d + 3)!)$</p> <p>else</p> <p style="padding-left: 20px;">$J \leftarrow (\mathbf{J}(y_{1:d}, d - 1, \epsilon) - \mathbf{J}(y_{0:d-1}, d - 1, \epsilon)) / (y_d - y_0)$</p> <p>end if.</p>
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Table 1: Pseudo-code for $J(y)$ with ordered input vector y .

Similarly,

$$\begin{aligned}
\frac{\partial^2 J(y_{0:d})}{\partial y_0^2} &= \lim_{\epsilon \rightarrow 0} \left(\frac{J(y_0 + \epsilon, y_{1:d}) - J(y_0, y_{1:d})}{\epsilon} - \frac{J(y_0, y_{1:d}) - J(y_0 - \epsilon, y_{1:d})}{\epsilon} \right) / \epsilon \\
&= 2 \lim_{\epsilon \rightarrow 0} \frac{J(y_0, y_0 + \epsilon, y_{1:d}) - J(y_0, y_0 - \epsilon, y_{1:d})}{2\epsilon} \\
&= 2 \lim_{\epsilon \rightarrow 0} J(y_0, y_0 - \epsilon, y_0 + \epsilon, y_{1:d}) \\
&= 2 J(y_0, y_0, y_0, y_{1:d}),
\end{aligned}$$

while

$$\begin{aligned}
\frac{\partial^2 J(y_{0:d})}{\partial y_0 \partial y_1} &= \lim_{\epsilon \rightarrow 0} \left(\frac{J(y_0 + \epsilon, y_1 + \epsilon, y_{2:d}) - J(y_0, y_1 + \epsilon, y_{2:d})}{\epsilon} \right. \\
&\quad \left. - \frac{J(y_0 + \epsilon, y_1, y_{2:d}) - J(y_0, y_1, y_{2:d})}{\epsilon} \right) / \epsilon \\
&= \lim_{\epsilon \rightarrow 0} \frac{J(y_0, y_0 + \epsilon, y_1 + \epsilon, y_{2:d}) - J(y_0, y_0 + \epsilon, y_1, y_{2:d})}{\epsilon} \\
&= \lim_{\epsilon \rightarrow 0} J(y_0, y_0 + \epsilon, y_1, y_1 + \epsilon, y_{2:d}) \\
&= J(y_0, y_0, y_1, y_1, y_{2:d}).
\end{aligned}$$

5 The special cases $d = 1$ and $d = 2$

For small dimension d it may be worthwhile to work with non-recursive implementations of the function $J(\cdot)$. Here we collect and extend some results of Dümbgen et al. (2007).

5.1 General considerations about a bivariate function

In view of (3) we consider an arbitrary function $f : \mathbb{R} \rightarrow \mathbb{R}$ which is infinitely often differentiable.

Then

$$h(r, s) := \begin{cases} \frac{f(s) - f(r)}{s - r} & \text{if } s \neq r \\ f'(r) & \text{if } s = r \end{cases}$$

defines a smooth and symmetric function $h : \mathbb{R}^2 \rightarrow \mathbb{R}$ such that

$$h(r, s) = f'(r) + \frac{f''(r)}{2}(s - r) + O((s - r)^2) \quad \text{as } s \rightarrow r.$$

Its first partial derivatives of order one and two are given by

$$\begin{aligned} \frac{\partial h(r, s)}{\partial r} &= \begin{cases} \frac{f(s) - f(r) - f'(r)(s - r)}{(s - r)^2} & \text{if } s \neq r, \\ \frac{f''(r)}{2} + \frac{f'''(r)}{6}(s - r) + O((s - r)^2) & \text{as } s \rightarrow r, \end{cases} \\ \frac{\partial^2 h(r, s)}{\partial r^2} &= \begin{cases} \frac{2(f(s) - f(r) - f'(r)(s - r)) - (s - r)^2 f''(r)}{(s - r)^3} & \text{if } s \neq r, \\ \frac{f'''(r)}{3} + \frac{f''''(r)}{12}(s - r) + O((s - r)^2) & \text{as } s \rightarrow r, \end{cases} \\ \frac{\partial^2 h(r, s)}{\partial r \partial s} &= \begin{cases} \frac{(s - r)(f'(r) + f'(s)) - 2(f(s) - f(r))}{(s - r)^3} & \text{if } s \neq r, \\ \frac{f'''(r)}{6} + \frac{f''''(r)}{12}(s - r) + O((s - r)^2) & \text{as } s \rightarrow r. \end{cases} \end{aligned}$$

The other partial derivatives of order one and two follow via symmetry considerations.

5.2 More details for the case $d = 1$

Recall that

$$J(r, s) = \int_0^1 \exp((1 - u)r + us) du = \begin{cases} \frac{\exp(s) - \exp(r)}{s - r} & \text{if } r \neq s, \\ \exp(r) & \text{if } r = s. \end{cases}$$

This is just the function introduced by Dümbgen, Hüsler and Rufibach (2007). Let us recall some properties and formulae for the corresponding partial derivatives

$$J_{a,b}(r, s) := \frac{\partial^{a+b}}{\partial r^a \partial s^b} J(r, s) = \int_0^1 (1 - u)^a u^b \exp((1 - u)r + us) du.$$

Note first that

$$J_{a,b}(r, s) = J_{b,a}(s, r) = \exp(r) J_{a,b}(0, s - r).$$

Thus it suffices to derive formulae for $(r, s) = (0, y)$ and $b \leq a$. It follows from (4) that

$$\begin{aligned} J_{a,0}(0, y) &= \int_0^1 (1 - u)^a \sum_{k=0}^{\infty} \frac{u^k}{k!} y^k du \\ &= \sum_{k=0}^{\infty} \frac{1}{k!} \int_0^1 (1 - u)^a u^k du \cdot y^k \\ &= \sum_{k=0}^{\infty} \frac{a!}{(k + a + 1)!} y^k \\ &= \frac{a!}{y^{a+1}} \left(\exp(y) - \sum_{\ell=0}^a \frac{y^\ell}{\ell!} \right). \end{aligned}$$

In particular,

$$\begin{aligned}
J_{1,0}(0, y) &= \frac{\exp(y) - 1 - y}{y^2} \\
&= \frac{1}{2} + \frac{y}{6} + \frac{y^2}{24} + \frac{y^3}{120} + O(y^4) \quad (y \rightarrow 0), \\
J_{2,0}(0, y) &= \frac{2(\exp(y) - 1 - y - y^2/2)}{y^3} \\
&= \frac{1}{3} + \frac{y}{12} + \frac{y^2}{60} + \frac{y^3}{360} + O(y^4) \quad (y \rightarrow 0), \\
J_{3,0}(0, y) &= \frac{6(\exp(y) - 1 - y - y^2/2 - y^3/6)}{y^4} \\
&= \frac{1}{4} + \frac{y}{20} + \frac{y^2}{120} + \frac{y^3}{840} + O(y^4) \quad (y \rightarrow 0), \\
J_{4,0}(0, y) &= \frac{24(\exp(y) - 1 - y - y^2/2 - y^3/6 - y^4/24)}{y^5} \\
&= \frac{1}{5} + \frac{y}{30} + \frac{y^2}{210} + \frac{y^3}{1680} + O(y^4) \quad (y \rightarrow 0).
\end{aligned}$$

Another general observation is that

$$\begin{aligned}
J_{a,b}(r, s) &= \int_0^1 (1-u)^a (1-(1-u))^b \exp((1-u)r + us) du \\
&= \sum_{i=0}^b \binom{b}{i} (-1)^i J_{a+i,0}(r, s).
\end{aligned}$$

In particular,

$$\begin{aligned}
J_{a,1}(r, s) &= J_{a,0}(r, s) - J_{a+1,0}(r, s), \\
J_{a,2}(r, s) &= J_{a,0}(r, s) - 2J_{a+1,0}(r, s) + J_{a+2,0}(r, s).
\end{aligned}$$

On the other hand,

$$\begin{aligned}
J_{a,b}(0, y) &= \sum_{k=0}^{\infty} \frac{y^k}{k!} \int_0^1 (1-u)^a u^{k+b} du \\
&= \sum_{k=0}^{\infty} \frac{a! [k+b]_b}{(k+a+b+1)!} y^k
\end{aligned}$$

with $[r]_0 := 1$ and $[r]_m := \prod_{i=0}^{m-1} (r-i)$ for integers $m > 0$. In particular,

$$\begin{aligned}
J_{1,1}(0, y) &= \frac{\exp(y)(y-2) + 2 + y}{y^3} \\
&= \frac{1}{6} + \frac{y}{12} + \frac{y^2}{40} + \frac{y^3}{180} + O(y^4) \quad (y \rightarrow 0).
\end{aligned}$$

5.3 The case $d = 2$

Our recursion formula (3) yields

$$J(r, s, t) = \begin{cases} \frac{J(s, t) - J(r, t)}{s - r} & \text{if } r \neq s, \\ J_{1,0}(r, t) & \text{if } r = s. \end{cases}$$

Because of J 's symmetry we may rewrite this in terms of the order statistics $y_{(0)} \leq y_{(1)} \leq y_{(2)}$ of $(y_i)_{i=0}^2$ as

$$J(r, s, t) = \begin{cases} \frac{J(y_{(1)}, y_{(2)}) - J(y_{(0)}, y_{(1)})}{y_{(2)} - y_{(0)}} & \text{if } y_{(0)} < y_{(2)}, \\ \frac{\exp(y_{(0)})}{2} & \text{if } y_{(0)} = y_{(2)}. \end{cases}$$

For fixed third argument t , this function $J(r, s, t)$ corresponds to $h(r, s)$ in Section 5.1 with $f(x) := J(x, t)$. Thus

$$\frac{\partial J(r, s, t)}{\partial r} = \begin{cases} \frac{J(s, t) - J(r, t) - J_{1,0}(r, t)(s - r)}{(s - r)^2} & \text{if } r \neq s, \\ \frac{J_{2,0}(r, t)}{2} + \frac{J_{3,0}(r, t)(s - r)}{6} + O((s - r)^2) & \text{as } s \rightarrow r. \end{cases}$$

Moreover,

$$\begin{aligned} \frac{\partial^2 J(r, s, t)}{\partial r^2} &= \begin{cases} \frac{2(J(s, t) - J(r, t) - J_{1,0}(r, t)(s - r)) - (s - r)^2 J_{2,0}}{(s - r)^3} & \text{if } r \neq s, \\ \frac{J_{3,0}(r, t)}{3} + \frac{J_{4,0}(r, t)(s - r)}{12} + O((s - r)^2) & \text{as } s \rightarrow r, \end{cases} \\ \frac{\partial^2 J(r, s, t)}{\partial r \partial s} &= \begin{cases} \frac{(J_{1,0}(r, t) + J_{1,0}(s, t))(s - r) - 2(J(s, t) - J(r, t))}{(s - r)^3} & \text{if } r \neq s, \\ \frac{J_{3,0}(r, t)}{6} + \frac{J_{4,0}(r, t)(s - r)}{12} + O((s - r)^2) & \text{as } s \rightarrow r. \end{cases} \end{aligned}$$

6 Gamma and multivariate beta (Dirichlet) distributions

Let G_0, G_1, \dots, G_m be stochastically independent random variables with $G_i \sim \text{Gamma}(a_i)$ for certain parameters $a_i > 0$. That means, for any Borel set $A \subset (0, \infty)$,

$$\mathbb{P}(G_i \in A) = \int_A \Gamma(a_i)^{-1} y^{a_i-1} \exp(-y) dy.$$

Now we define $a_+ := \sum_{i=0}^m a_i$, $G_+ := \sum_{i=0}^m G_i$ and

$$\tilde{\mathbf{B}} := (G_i/G_+)_{i=0}^m, \quad \mathbf{B} := (G_i/G_+)_{i=1}^m.$$

Note that $\tilde{\mathbf{B}}$ is contained in the unit simplex in \mathbb{R}^{m+1} , while \mathbf{B} is contained in the open set $\mathcal{T}_m = \{\mathbf{u} \in (0, 1)^m : u_+ < 1\}$ with $u_+ := \sum_{i=1}^m u_i$. We also define $u_0 := 1 - u_+$ for any $\mathbf{u} \in \mathcal{T}_m$.

Lemma 6.1. *The random vector \mathbf{B} and the random variable G_+ are stochastically independent. Moreover,*

$$G_+ \sim \text{Gamma}(a_+)$$

while \mathbf{B} is distributed according to the Lebesgue density

$$f(\mathbf{u}) := \frac{\Gamma(a_+)}{\prod_{i=0}^m \Gamma(a_i)} \prod_{i=0}^m u_i^{a_i-1}$$

on \mathcal{T}_m . For arbitrary numbers $k_0, k_1, \dots, k_m \geq 0$ and $k_+ := \sum_{i=0}^m k_i$,

$$\mathbb{E}\left(\prod_{i=0}^m B_i^{k_i}\right) = \frac{\Gamma(a_+)}{\Gamma(a_+ + k_+)} \prod_{i=0}^m \frac{\Gamma(a_i + k_i)}{\Gamma(a_i)}.$$

As a by-product of this lemma we obtain the following formula:

Corollary 6.2. *For arbitrary numbers $a_0, a_1, \dots, a_m > 0$,*

$$\int_{\mathcal{T}_m} \prod_{i=0}^m u_i^{a_i-1} d\mathbf{u} = \Gamma(a_+)^{-1} \prod_{i=0}^m \Gamma(a_i).$$

Proof of Lemma 6.1. Note that $\mathbf{G} = (G_i)_{i=0}^m$ may be written as $\Xi(G_+, \mathbf{B})$ with the bijective mapping $\Xi : (0, \infty) \times \mathcal{T}_m \rightarrow (0, \infty)^{m+1}$,

$$\Xi(s, \mathbf{u}) := (su_i)_{i=0}^m.$$

Note also that

$$\det D\Xi(s, \mathbf{u}) = \det \begin{pmatrix} u_0 & -s & -s & \cdots & -s \\ u_1 & s & 0 & \cdots & 0 \\ u_2 & 0 & s & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & 0 \\ u_m & 0 & \cdots & 0 & s \end{pmatrix} = \det \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ u_1 & s & 0 & \cdots & 0 \\ u_2 & 0 & s & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & 0 \\ u_m & 0 & \cdots & 0 & s \end{pmatrix} = s^m.$$

Thus the distribution of (G_+, \mathbf{B}) has a Lebesgue density h on $(0, \infty) \times \mathcal{T}_m$ which is given by

$$\begin{aligned} h(s, \mathbf{u}) &= \prod_{i=0}^m (\Gamma(a_i)^{-1} \Xi(s, \mathbf{u})_i^{a_i-1} \exp(-\Xi(s, \mathbf{u})_i)) \cdot |\det D\Xi(s, \mathbf{u})| \\ &= \prod_{i=0}^m (\Gamma(a_i)^{-1} (su_i)^{a_i-1} \exp(-su_i)) \cdot s^m \\ &= s^{a_+-1} \exp(-s) \prod_{i=0}^m (\Gamma(a_i)^{-1} u_i^{a_i-1}) \\ &= \Gamma(a_+)^{-1} s^{a_+-1} \exp(-s) \cdot f(\mathbf{u}). \end{aligned}$$

Since this is the density of $\text{Gamma}(a_+)$ at s times $f(\mathbf{u})$, we see that G_+ and \mathbf{B} are stochastically independent, where G_+ has distribution $\text{Gamma}(a_+)$, and that f is indeed a probability density on \mathcal{T}_m describing the distribution of \mathbf{B} .

The fact that f integrates to one over \mathcal{T}_m entails Corollary 6.2. But then we can conclude that

$$\begin{aligned}\mathbb{E}\left(\prod_{i=0}^m B_i^{k(i)}\right) &= \int_{\mathcal{T}_m} \prod_{i=0}^m u_i^{a_i+k_i-1} d\mathbf{u} / \int_{\mathcal{T}_m} \prod_{i=0}^m u_i^{a_i-1} d\mathbf{u} \\ &= \frac{\Gamma(a_+)}{\Gamma(a_+ + k_+)} \prod_{i=0}^m \frac{\Gamma(a_i + k_i)}{\Gamma(a_i)}.\end{aligned}$$

□

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